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FIRE SAFETY ENGINEERING AND SUSTAINABLE DEVELOPMENT

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ABSTRACT

This paper discusses the concept of fire safety engineering in the context of rapidly developing South Asian countries. It is highlighted that fire safety system design is only one part of the process – the design needs to be analysed to demonstrate that it can achieve acceptable level of fire safety. South Asian countries are also facing the consequence of climate change and energy demand challenges and therefore, there is a motivation for sustainable constructions. However, sustainable construction often leads to fire safety risks with recent Grenfell Tower disaster in London. Sprinkler is one of the most effective fire safety system that contributed to no fatality in Lacrosse building in Melbourne. Victoria University's research program on water-based fire suppression system (sprinkler and water mist) are presented. Computational fluid dynamics based fire model used for building fire growth, propagation and suppression is now being used for wildfire modelling by Victoria University's research team. Although wildfire is not a major threat for tropical forests, with the climate change and longer dry weather are making it a possibility. Tropical nations need to be prepared for it and work towards risk reduction.

Keywords: *Fire safety engineering, risk management, design adequacy, exit path, sprinkler.*

1. INTRODUCTION

Once a nation well advances into development or get industrialized, its human capital becomes important. It is well known that in poorer countries, families have more children and on the other hand, families in the developed nations have less number of children. Roughly when a nation/region reaches a fertility rate below 3.0, it starts focusing on human development and each individual becomes a valuable asset for the country. Safety of this human capital becomes a priority for the nation and the safety starts with the building code. For example the first such national document in Australia was referred to as the "Australian Model Uniform Building Code" (AMUBC), which was first released in the early 1970's. However, individual states started developing their own codes after World War II particularly focusing on technical building requirements, rather than on the safety of occupants and emergency services personnel (Australian Building Code Board, 2017). However, in UK, as a result of the great fire in London in September 1666, some fire safety provisions were regulated. Once again those were for property protection, rather than for the life safety as the death toll was quite small compared to the massive destruction it created.

South Asia's fertility rate starts falling below 3.0 from the beginning of this millennium and at the same time all South Asian countries started to make their journey of economic prosperity. Unfortunately many of these progresses took place at the expense of poor workers' health, safety and life style. It is the beginning of this decade, the safety culture in South Asian countries started to improve. In Bangladesh, it is triggered by Tazreen Fashion factory fire in 2012 (BBC, 2017). Since then enormous progress has been made in the garments sector in relation to fire safety.

Since the South Asian countries are progressing economically, in natural process, housing construction will not be merely a basic amenity. With the threat of climate change and energy security are emerging, in the developed world the focus is on energy efficient construction. This is proving to be a challenge for fire safety as many of these energy efficient materials are highly combustible and due to the insulation property, the room of fire ignition can be heated up very quickly. Fire safety does not only encompass structural sustainability or business continuation, the major focus these days is the safety of the occupants and fire fighters. Knowledge of the behaviour of materials and structures, heat and mass transfer, hydraulic and mechanical systems, human behaviour and fire dynamics all form important parts of fire safety engineering. In this article, the challenge of achieving fire safety while having sustainable construction will be discussed. In addition, various fire safety research programs being carried out at Victoria University will be presented.

2. CONCEPTUAL FRAMEWORK OF FIRE SAFETY AND ITS ENGINEERING

To combine technological advancement, quality of life and energy and economic challenges, a new discipline emerged in early 90s to enable the design of buildings and infrastructure for fire safety beyond the prescriptive provisions of the Building Codes. This is known as Fire Safety Engineering which can be described as a branch of engineering that uses engineering and scientific principles from a range of disciplines to fire safety design for buildings and infrastructure. It is often considered that prescriptive requirements are unnecessarily onerous, imposing a financial burden on developer and owners without achieving much fire safety (Bennetts, Moinuddin, Goh and Thomas, 2005). These requirements may be developed based on engineering judgment rather than scientifically. Furthermore, often technology advancement occurs much faster than the legislating the application of those prescriptively. Therefore the building codes of the most developed countries have a provision of alternative (fire safety engineering) solution (Australian Building Code, 2016; New Zealand Building Code, 2014). These solutions are alternative to prescriptive solutions mentioned in the building codes and also known as performance-based design (achieving quantified targeted risk). Performance-based design has now become the method preferred by fire safety engineers. This is driven by the flexibility offered to the user to adopt their new design concept without compromising safety aspects required by regulations.

2.1 Systematic *Approach*

It is important to have a systematic approach to Fire Safety in which fire risks need to be identified. In this approach the risk management process (as defined and described in AS/NZS 4360-2004 Risk Management (Standard Australia 2004) and AS/NZS ISO 31000 Risk management (Standard Australia 2004)) are usually adopted. The process consists of several steps which are undertaken in sequence, with several other activities that contribute to the whole process and which may contribute to each of the steps that should be undertaken continually to ensure that the context is continually monitored and updated, the people involved in the process are consulted with clear two-way communications and the process and outcomes are continually reviewed to ensure that they are, and remain, satisfactory and appropriate.

Risk, in this context, is defined in (Standard Australia 2004) as "*The chance of something happening that will have an impact upon objectives. It is measured in terms of consequences and likelihood."* The sequential steps involved in the process are briefly described as follows:

- Establish the Context: ensure safety of the occupants and fire fighters, structural sustainability, business continuation etc.
- Risk Identification
  - This step is intended to identify the hazards (risks) using a well-structured systematic process.
  - All hazards, whether or not under the control of organization, should be included, as hazards not identified at this stage are not considered in subsequent steps.

  - For each hazard, identify what the hazard is and why and how it can occur, as the basis for further analysis.
- Conduct Risk Analysis: entails identification of threats likely to prevail and consideration of the:
  - use of the building
  - characteristics of its occupants
  - potential for fire growth
  - passive and active protection needs
  - facilities available for occupant avoidance of hazards, and
  - availability of fire fighting resources.
- Conduct Risk Evaluation:
  - This step is intended to determine fire risk management priorities by comparing the estimated level of risk against predetermined standards (such as level of fire deaths/ injuries in developed countries), setting a target risk levels etc.
  - The hazards (risks) may also be ranked so as to establish management priorities.
  - If the risk level due to a specific hazard is low enough, then it may be considered acceptable and treatment for that specific may not be required.
- Consider Treatment of Risks
  - For hazards other than those considered acceptable this step is intended develop and implement appropriate plans (actions) for reducing or eliminating the risk associated with each hazard.
  - For each hazard implement a specific management plan which includes consideration of priorities and available resources.

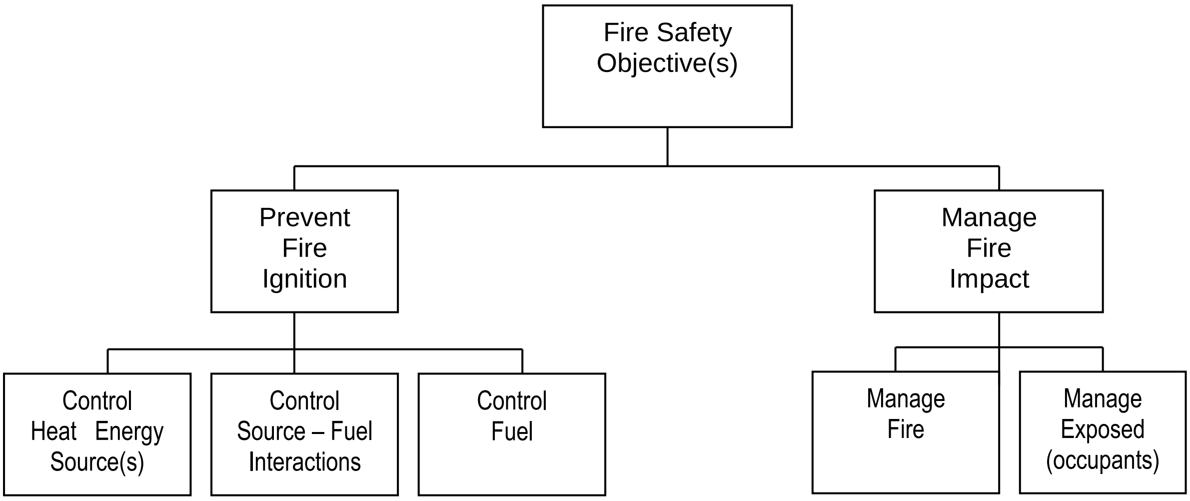


Figure 1. NFPA 550 fire safety concept tree (National Fire Protection Association, 2017)-additional major branch “Administration” is not shown

2.2 Fire Safety System Design Process

In light of risk management approach, the following steps need to be undertaken:

- Objectives must be agreed upon (establish the context)
- Identify risks/hazards to achieve objectives (risk analysis)
- Set an acceptable risk target. Zero risk can’t be achievable; as no society has unlimited resources to achieve it let alone a developing region like South Asia.
- Design strategies to mitigate risks:
  - Prevent fire ignition
  - Control combustion process
  - Control fire by construction
  - Detect fire early and provide notification

- Automatically suppress fire
- Manually suppress fire
- Manage exposed (people or physical objects)

2.3 FPA Concept Tree for Mitigating Risk

NFPA 550 concept tree (National Fire Protection Association, 2017), presented in Figure 1, is designed to avoid pervious omissions and fire safety weakness. It stipulates that fire safety objectives can be achieved by the followings:

a. Fire prevention: isolation of ignition source and/or fuel and prevent their interaction. From the statistics (Fire Service and Civil Defence, 2010) it is learned that nearly 40% of the fires in Bangladesh were due to the electrical faults. Therefore electrical safety appears to be of paramount important.
b. Fire Management: it falls into two main categories:
    - Managing fire which falls into three main parts:
        - Suppress fire by sprinkler, water mist, fire extinguisher etc
        - Control fire by construction: in controlling fire by construction, the designer
            - seeks to control the movement of fire, and
            - provide structural stability.
        - Control smoke by smoke extraction fan, natural vent etc.
    - Managing the exposed (i.e. building occupants): by providing
        - Smoke, heat or flame detectors,
        - Intercom alarm system, and
        - Providing flame and smoke free evacuation path.
c. Administration: Periodic inspection of Fire Safety Systems' serviceability and conduct of evacuation drill.

2.4 How Do We Know Design Adequacy

Anecdotal evidence suggests that higher rate of fires occur in prescriptively designed buildings than performance-based designed building. Therefore regulatory authorities around the world are contemplating to introduce risk-informed design. This implies that whether prescriptive or performance-based, the quantified risk to the building must be assessed. Risk is often calculated as the product of probability and consequence. Probability is determined by statistical data and reliability studies.

To assess the consequence to the fire safety system of the building must be tested against a range of credible sized fires:

- Will the building structure survive intense heat?
- Will the heat, radiation and toxicity in building and its evacuation path reach to a point when occupants and fire fighters die?
- Once fire is detected, will the occupants able to evacuate safely?

This assessment can be conducted with two approaches:

- Experimental: By conducting full-scale experiments on a typical floor built and furnished exactly the same way as the designed building anticipated to be. 140 William St of Melbourne was such an experimental program (will be discussed in Section 4.2).
- Computational: As the experimental program is very expensive, fire safety engineers these days uses a number of advanced computational software:
    - For structural analysis finite element based software,
    - For flame & smoke propagation simulation computational fluid dynamics software
    - For evacuation modelling numerical algorithm for human movement speed through open space, corridor, stair etc, possibility of bottleneck etc are used.

With the assessment from either of the two or combined approaches, fire safety engineers primarily determines whether occupants can safely evacuate from the building or some of the get trapped and suffers injury / death. The basic principle to determine whether the building has been adequately designed for fire safety is:

Available Safe Evacuation Time > Required Safe Evacuation Time

Although occupant safety is the major concern, it is not the only objective to be met. Whether other objectives such as firefighter safety, structural sustainability, business continuation etc. are met can be determined by other agreed criteria. The method of conducting assessment of the building fire safety system against a range of credible sized and demonstrating that objectives can be met in all these fire scenarios is known as deterministic approach. However in reality there can be 100s of fire scenarios with various probabilities (usually larger sized fires have low probability). Furthermore, often it is assumed in deterministic approach that reliability of fire safety provisions are not considered except in form of sensitivity analysis. Therefore a more advanced method known as Probabilistic Risk Analysis is occasionally adopted for very large projects. In this approach:

- The probability of having large, medium and small fires is taken into account.
- Reliability of various fire safety system is considered

3. SUSTAINABLE DESIGN AND FIRE SAFETY

According to (Komiyama and Takeuchi, 2006), there are three major aspects of sustainability: global, social and human. Hidalgo (2015) summarised them as follows:

- the global aspect is related to the preservation of the planet and therefore the human survival (energy preservation, reduction of CO_2 emission to prevent climate change, ecosystems preservation, etc.),
- the social aspect encompasses the political, economic and technological factors such as mass production of low cost housing, prefabricated construction etc for providing housing for peoples of all economic background
- human factors are related to comfort (thermal), lifestyle (aesthetic design, soundproof), security from natural hazards (wildfire, flood, cyclone) etc.

To achieve the above sustainability goals, energy efficient building materials are now being used across the world. Plastic-based materials due to its lower thermal conductivities compared to non-combustible can provide better thermal comfort, but poses greater fire risk due to its combustibility. Hidalgo (2015) also summarised the main features and concepts for energy efficient buildings as shown below:

- High levels of insulation materials in the envelope of the building.
- Increased levels of air tightness.
- Efficient heat recovery of the ventilation in order to improve the performance of heating and cooling systems.
- Reduction of thermal bridging.
- Use of more efficient windows.

Insulation materials can be installed within the wall system or as external façades. Many of these also serve the purpose of sound-proofing (from traffic noise, noise from adjacent buildings etc). External façades additionally provide aesthetic. Two types of common insulators have been identified in construction over recent decades (Hidalgo, 2015): non-combustible inorganic materials such as glass wool (GW) and stone wool (SW) and combustible plastic-based materials such as Polyurethane rigid foam (PUR), polyisocyanurate rigid foam (PIR), rigid phenolic foam (PF) and expanded polystyrene (EPS). Critical temperature for fire ignition for PIR and PF are 300°C and 425°C, respectively. The critical temperature for EPS is 240°C, which is its melting point (Hidalgo, 2015). PUR's auto ignition point is between 370°C to 427°C (Material Information Data Sheet, 2013). Aluminium composite materials (ACM) are another kind of façade materials which comprise two metal skins (normally of aluminium) bonded on to a core of sheet material such as polyethylene core. Commercial grade polyethylene melts at *105-180*°C (depends on the density) and can catch fire easily.

To increase the fire performance, the polymeric industry needs to formulate plastics (Hidalgo, 2015) with:

- Reduced flammability (with performance criteria on the basis of a series of standard tests).
- Higher thermal stability (defined as increased char content and delay on the onset of thermal degradation).

Meacham et al (Meacham, Poole, Echeverria and Cheng, 2012) provided a list of fire incidents which were caused by combustible insulation materials as well as commercial photovoltaic panel fire incidents. Two recent fire incidents are described in Table 1. Both buildings used ACM. However, due to poorer fire safety engineering design and strategy, 71 people died in Grenfell Tower compared to none in Lacrosse Building. Fire suppression system, building-wide alarm and additional evacuation stair resulted in saving all lives. Water-based fire suppression system is a major stream of research at Victoria University.

Table 1: Comparing Grenfell vs Lacrosse fires

Parameters	Grenfell Tower London (2017)	Lacrosse Melbourne (2014)
Type	High-rise residential	High-rise residential
Floors	24	23
State of occupants	Asleep	Asleep
Fire brigade	Within minutes	Within minutes
Cladding	Twin aluminium sheet, 3 mm thick, with polyethylene core	flammable aluminium composite cladding
Fire safety measures	No sprinklers, No building-wide alarm	Sprinklers Building-wide alarm
Exit stairs	1	2
Evacuation strategy	*'Stay put'*	*Immediate*
Fatality	*71*	*0*

4. FIRE SUPPRESSION RESEARCH

Water is an excellent heat absorber and environment friendly. Automatic sprinkler and water-mist are two commonly used water-based fire suppression system. In addition fire fighters also use water for supressing the fire. In sprinkler and water-mist systems, water is supplied through a system of piping, valves and pumps and are arranged so that they are able to automatically distribute sufficient water directly to a fire to control/extinguish it. For the sprinkler, this is achieved by cooling the fire and wetting surrounding materials in order to make them harder to ignite. For water mist system, additionally the displacement of oxygen by means of evaporation of water droplets also occurs. As a consequence of these applications of water, the water interferes with the combustion process sufficiently to reduce the size of the fire and possibly extinguish it.

Compared to the conventional water sprinkler droplets (1000 – 5000 µm), the water-mist nozzle uses smaller droplets of water (diameter≦1000 µm). The effectiveness of a fire-safety system can be considered as the product of its *efficacy* and its *reliability.* A number of studies have been conducted in relation to efficacy, reliability and capability of numerical modelling of these systems at Victoria University.

4.1 Sprinkler Reliability

Fault tree analysis (FTA) is an effective way of estimating reliability of a system. The basis for FTA is a logical structure which describes the causal relationship between the basic hardware, human, and environmental events resulting in system failure. FTA works with backward logic. Given a particular failure of a system (known as the top event), FTA identifies which component failure of the system leads to the top event. The logical connections between the events are made by event statements and logic gates. Based on the failure probability of each component, the failure probability (i.e. lack of reliability) of the top event can be calculated. Failure probability of each component can be calculated using a physical survey.

A downfeed sprinkler system is shown in Figure 2. Like tridents, tappings are taken from each water main and are used to transfer water for normal supply, sprinklers and fire hoses. For sprinklers, water is drawn and either supplied directly to the pump or stored in basement reservoirs/tanks and then is pumped to the riser. Water flows through non-return valves, pump isolation valves, the main sprinkler valve and then alarm valves to the riser. From the riser through a piping networks water is supplied to the sprinkler heads and the system is permanently kept under pressure. Once a sprinkler head is activated due to the water release through the orifice, pressure drops. As a result the alarm valve opens, pressure switches activate the pumps and water flows through the alarm valve. While water flows through the alarm valve, an alarm sounds to the fire brigade and to the building. A pump bypass system is usually provided to provide water under mains pressure to the lowest zone in the building, as a back-up supply. This system supplies water to only a few storeys (usually a maximum of eight). A set of *very high pressure single stage* pumps directly supplies water to the gravity tank placed at the top of the building. However if the pressure requirement is high *two stage* pumps should be used (*single stage* pumps can approximately reach 24 bar or 2.4 MPa maximum pressure whereas a *two stage* pump can reach 41 bar or 4.1 MPa). In each plant room a set of pressure reducing valves are installed to regulate the water pressure appropriately for the sprinklers and piping system in the stage below. Alternatively a pair of cell tanks, storing required amount of water, from which water is supplied for the lower stage, are installed. A fault tree of the sprinkler system of a 60 storey building shown in Figure 2 was constructed and can be found in Moinuddin and Thomas (2014). A number of assumptions in constructing the fault tree were made and can be found in (Moinuddin and Thomas, 2014).

A comprehensive survey of sprinkler systems in high-rise office buildings was carried out to determine the reliability of various components of such systems in Australia. Based on the survey data, the overall reliability of these sprinkler systems were estimated. Although it was challenging to involve the building owners in the study, it was possible to collect significant amount of data by consulting relevant documents of 29 participating buildings. In addition, data from overseas surveys has also been considered based on their relevance to the office buildings. The analyses were confined only to wet-pipe systems, as these constitute the vast majority of automatic sprinkler systems in warm countries.

Out of 21 components, 14 components data are found to be within the same order of magnitude of the data found in the literature. The remaining 7 components' failure probabilities are found to be higher than in the literature. Using sensitivity analysis of the fault tree it is apparent that the top event is very sensitive to the failure probability of the following components:

- Sprinkler head
- Non-return valve
- Pressure switch
- Gravity tanks
- Alarm valve
- Zone isolation valve
- Pressure reducing valve

However, both survey and literature data reveal that the failure probability of these components is very small except for the sprinkler head and zone isolation valve (sprinkler downtime due to work during tenancy change). These two most important issues will be now discussed in detail. However, it is assumed in regulatory and building management circles that if the strict maintenance regulation and practice are not continued, the failure probability of other components is likely to rise significantly.

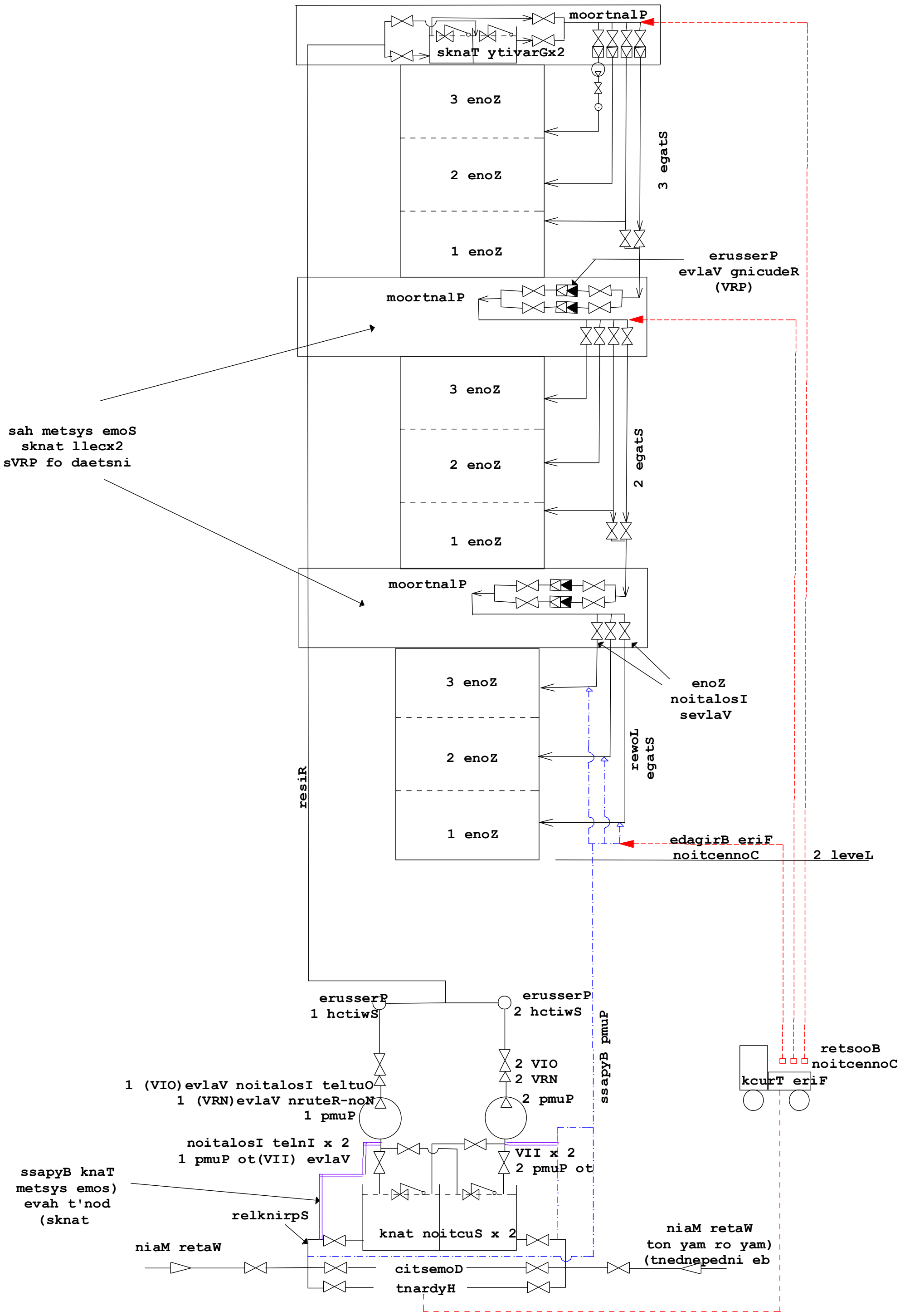


Figure. 2 Details of water supply and sprinkler system for a 60 storey building (downfeed system) from (Moinuddin and Thomas, 2014).

The reliability of the sprinkler system is estimated based on a number of considerations (upfeed vs downfeed, data of mean, 95% confidence and 5% confidence level, number of heads required to be failed etc). It can be observed that the failure probability of the sprinkler system in a 60 storey Australian office building lies in the range 3% to 14% within which the commonly considered value (5%) in Australia falls. Sprinkler zone shut off during tenancy changes and sprinkler head failure appear to be the main factors that may lead to a sprinkler system failure. Sprinkler head failure can be reduced by more frequent periodic inspection and sprinkler downtime can be reduced by the following means:

- Installing sprinkler isolation valve for each floor

- Use of flexible pipes connecting the riser and sprinkler head. This will result in relocating sprinkler heads without isolating the system for minor change of office.

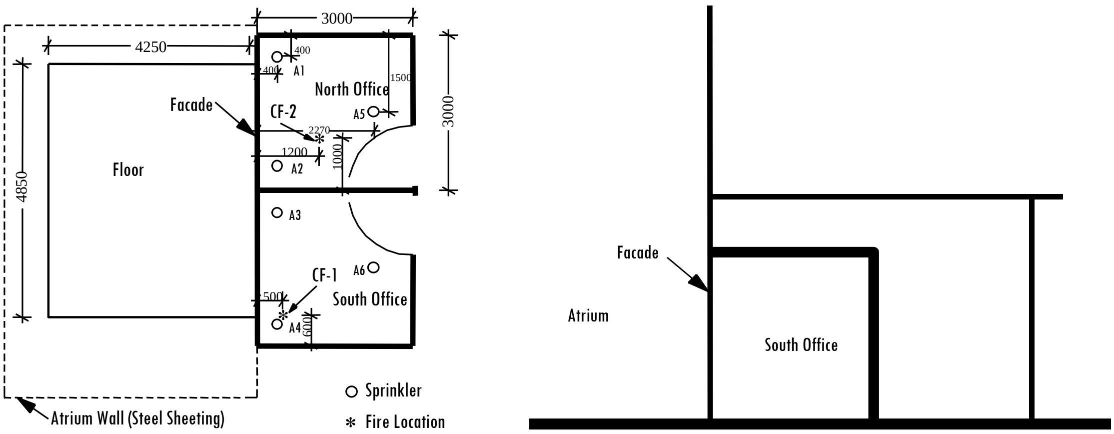
4.2 Sprinklered office fire

In this research project, the efficacy of sprinkler systems in various office building situations has been tested extensively, both individual and open-plan office situations (Bennetts et al, 2008). The tests subjected the structural steelwork and composite floor slab, which make up the load bearing components of the building, to realistic fire and gravity loads. The tests provided data on sprinkler activation and fire suppression times for a range of real fire situations and a range of sprinkler heads and pressure/flow conditions. Temperatures of steelwork as well as air temperatures, away from the workstation on fire, were recorded at numerous locations around the building. In some situations, smoke detectors were also included in the tests and their performance is also reported.

(a) (b) (c)

Figure 3: Photos of Capita Façade tests (a) Exterior to test structure as viewed from East, (b) Office set up adjacent to the façade and (c) Typical fire load

The first set of tests were conducted in a modified building shown in Figure 3*(a)*. The upper level construction was prepared to study the ability of sprinklers to extinguish fires in individual offices close to the glass façade forming one wall of the atrium. The atrium space was enclosed with steel sheeting and a glass façade. The offices were separated from the simulated atrium enclosure by the glass façade (Figure 3*b*). The offices were furnished as a typical office and incorporated a combination of paper, timber and plastic furniture, nylon carpet, curtains and vinyl wall paper as shown in Figure 3*(c)* These tests are referred to as the “Capita Facade” tests and refer to the name of the building project for which the testing was undertaken. Four fire tests were conducted in the offices as part of this testing program. A plan and elevation showing the two offices in relation to the atrium space are shown in Figure 4 and the sprinkler heads positioned as shown for the two representative tests.



(a) Plan view *(b)* Elevation view

Figure 4: Sprinkler locations during Capita Façade tests and elevation view.

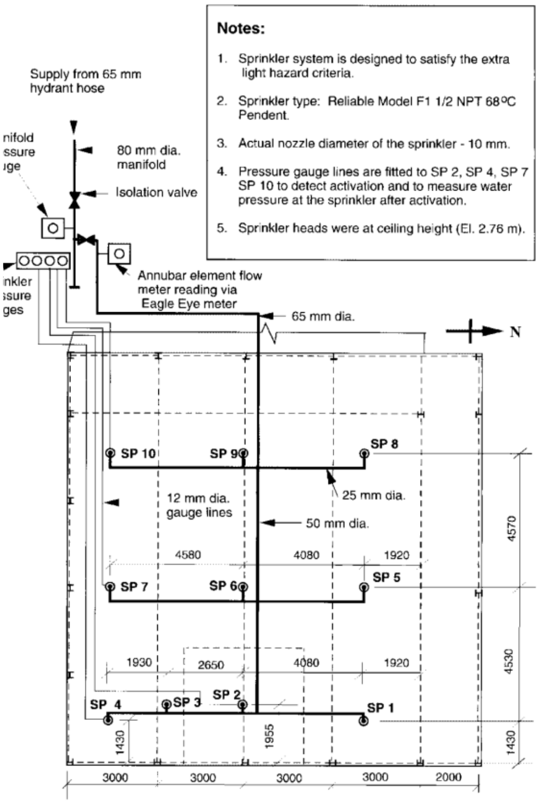
The size of the fire at the time of sprinkler activation and the damage that occurred for each of the tests are shown in Figure 5. Photographs of the fire scenarios were taken by a camera focused through the façade from the atrium side. Photographs of the extent of damage were taken after each fire from within the room. Based on the conduct of similar experiments under a calorimeter it is estimated that these fires corresponded to heat release rates at the time of sprinkler activation of approximately 25-85 kW. Glass façade temperature did not exceed 24°C and fire was suppressed within 17 seconds of sprinkler activation.

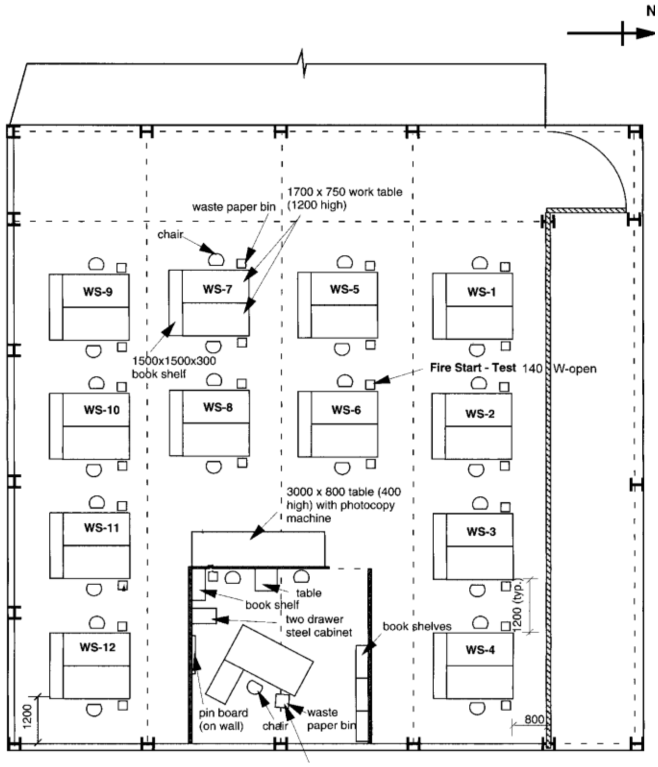
Figure 5. Size of the fire at time of sprinkler activation and resulting damage during Capita Façade tests

In the second series of tests, a set of open-plan office experiments were conducted with an open plan office space was fitted out with 29 representative workstations as shown in Figure 6. This series was conducted for the 140 William St project in Melbourne. These tests included a sprinklered test in a small office (hereafter referred to as 140W-small) and an open-plan test (140W-open). For the series, two of the perimeter walls of the tested area were glazed (east and south walls) with the other sides being a combination of steel sheeting and concrete, or simply steel sheeting. The glazed parts consisted of 10mm plate glass over the floor-to-ceiling height. The small office used for 140W-small was positioned adjacent to the east glazed façade (see Figure 6*b*) and was formed with two plasterboard walls and one glazed interior wall containing a door. Sprinkler system, indicative floor plan and the points at which the fire was initiated are given in Figure 6.

Similar to the Capita Façade tests, the small office was fitted out as a typical office of 80s and 90s and incorporated a combination of paper (books, drawings, magazines etc.), timber and plastic furniture and acrylic based plastic carpet (see Figure 7a). The wood equivalent fire load in the 140W-small test was 52 kg/m^2. In all these tests fire was initiated by setting fire to a plastic waste paper basket placed under the desk but directly adjacent to a padded chair. The open plan area of the building for 140 William St was furnished to resemble a crowded but otherwise normal office environment as shown in Figure 7(b). The fire load consisted of desks with side returns, bookcases, chairs and credenzas (low cupboards). The desks and bookcases contained large amounts of combustible materials including drawings, books, magazines and plastic coated folders.

During 140W-small test, a single sprinkler (SP2 in Figure 6*a*) operated about 7 minutes and 10 seconds from first ignition from a waste paper bin. About 20 seconds after the sprinkler operated the fire had clearly been controlled although a small pocket of flame was visible in an area protected by the chair. The contents of the small office were largely undamaged and the contents of the open plan area were not noticeably damaged. Items damaged by the fire in the small office were the waste paper bin and its contents and the adjacent chair and desk (see Figure 7*c*). The ceiling tiles directly above the fire were slightly discoloured. A person entered the small office again 10 minutes and 40 seconds after the start of the fire without discomfort and extinguished the few remaining burning elements by a hand extinguisher.





(a) Sprinkler system (b) Indicative flor plan and ignition points

Figure 6: 140 William St. Tests

During 140W-open test, the fire was initiated at the location shown in Figure 6*b*. 6:19 minutes from the start of the test 4 sprinklers opened in rapid succession and quickly extinguished the fire. The 4 sprinkler heads closest to the fire opened (numbers SP5, SP6, SP8 and SP9 in Figure 6*a*). Only the bin and desk directly above it (including its contents) were burnt (see Figure 7*f*). The chair at the adjacent desk was damaged and blackened by the fire but it had not begun to flame when the sprinklers operated. The ceiling of the open plan area was heavily discoloured over a large area.

The fire at the time of sprinkler activation for each of the tests is shown in Figures 7*(c)* and 7*(d)*. Based on the conduct of similar experiments under a calorimeter and a careful study of video records of these fires it is estimated that these fires corresponded to heat release rates at the time of sprinkler activation of approximately 0.3 and 1.5 MW respectively.

There were two more series of tests conducted. In all cases, when the sprinkler was operated, the sprinkler system was effective in controlling the fires in both the small and open plan office settings and little damage resulted. There was no damage to the building or small office other than the effect of small amounts of smoke and water. Neither the exterior nor interior windows of the buildings were cracked or damaged. The steel structure of the buildings was not affected at all. The time of automatic operation of the sprinklers was such that the occupants of an open plan office area of similar dimensions would not have suffered any significant distress or permanent harmful effects provided they were reasonably mobile.

Significant amount of quantitative data of air, steel and glass temperatures, radiation heat flux and concentrations of CO and O_2 was collected during the tests as presented in (Bennetts, Moinuddin, Proe and Thomas, 2008). Data provided by these tests will prove useful for fire safety engineering professionals and those concerned with assessing the efficacy of sprinklers and the effects of sprinklered fires in buildings. The outcomes from these tests can also be used to develop rational performance-based designs.

Figure 7. The fire load and size of the fire at the time of sprinkler activation during 140 William St. tests and damage estimate after fire.

4.3 Water-mist

Water mists are sprayed from a nozzle under high pressure. In this system, very small amounts of water can be used to extinguish fires rather than resorting to the historical "drowning" techniques. Water mist system can be used for environmentally sustainable design (ESD) building as the system can reduce water damage in the event of a fire. In the ESD front, another application is replacing halon 1301 (bromo-tri-fluoro methane, CF_3Br) as the primary fire-fighting agent for protecting the machinery spaces of ships. Halon 1301 is not only harmful to humans, but it also depletes the ozone layer. Additionally, entrainment of mist into fire plume allows to partially extinguish concealed fire – another advantage over conventional sprinkler system. Currently they are used in archives, libraries, hospitals, tunnels, engine room, machineries room etc. However the system can be expensive due to the use of high pressure pump and stainless steel pipes and at the same time can be less reliable than the sprinkler due to having more complex system. The motivations of water-mist research at Victoria University is driven by its potential use in marine vessel (both merchant and naval) applications as well as application in tunnel (collaboratively with University of Fukui, Japan) for fire suppression.

It is essential to examine the efficacy of water-mist droplets in suppressing fires. The efficacy of a water-mist system can be investigated in two ways: (i) experimental investigation; and (ii) numerical analysis. As the experimental study is very expensive, numerical modelling is favoured. However, numerical models need to be validated against the benchmark experimental studies before being used for design purposes. Our study involves conducting experimental studies, validating stat-of-the art numerical models (computational fluids dynamics, CFD, based fire model) and use of the numerical models for understanding many physical phenomena.

We endeavour to extend and refine the Fire Dynamics Simulator (FDS) developed by NIST (McGrattan et al., 2013) for building fire and its sister model for wildfire Wildland-Urban Interface Fire Dynamics Simulator (WFDS). The uniqueness of this model is its pyrolysis model, which allows fire growth and suppression modelling. FDS is fundamentally a finite difference approximation to the equations of fluid motion. That is, the computational domain is discretised into cells or control volumes. The set of partial differential equations for the conservation of mass, momentum and energy for a Newtonian fluid are solved by the FDS model. The FDS/ WFDS solves numerically a form of Navier-Strokes equation appropriate for low Mach number, thermally-driven flow (Mach number < 0.3) with an emphasis on smoke and heat transport from fires.

In this paper, the results of distribution of flux densities of water-mist nozzle sprays from a set of benchmark experiments and FDS modelling are presented. The effectiveness of a spray in suppressing a fire is greatly influenced by its distribution pattern on a horizontal surface. Hence, it is essential that any CFD based model can predict the distribution of the flux densities of a spray. Full-scale experiments have been conducted on water sprays emanating from a single and multi-orifice nozzle, and the distributions of flux densities have been measured. Numerical simulations have been performed using FDS.

An experiment rig was constructed to measure the distribution of flux density produced by the sprays. This was achieved by placing a 2✕2✕0.1 m water collection tray beneath the nozzles. To spatially resolve the distribution of flux density the tray was divided into 400 compartments, each with dimensions of 10✕10✕10 cm. The single-orifice and the multi-orifice nozzle heads were clamped at heights of 2.3 m and 2.0 m, respectively, above the floor. Water was supplied to the nozzles by means of a pump that could operate at a pressure of up to 400 bar. The experimental rig is illustrated in Fig 8 (Mahmud et al, 2016).

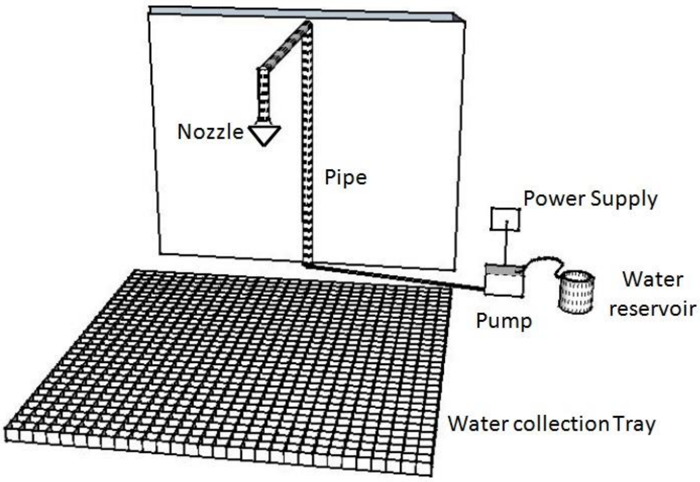


Figure 8: Schematic view of the experimental set-up from (Mahmud et al, 2016).

Two types of nozzles were used in the experiments: (a) single-orifice nozzle and (b) multi-orifice nozzle with six orifices at the periphery and one at the centre. The angles of the sprays for both of the nozzles were determined from the photographs of sprays. The parameters of the spray, i.e. water flow rates, spray angles and spray heights of the experiment were used as input parameters in FDS model. Only the multi-orifice case is presented here. Two experiments with the multi-orifice nozzle were carried out placing the multi-orifice nozzle head: (1) above the centre (like Figure 9a) and (2) above one of the corner of the water collection tray array (Figure 9b). In all cases, a boundary wall was located at 2 m away from the nozzle head –which was a limitation of the study.

In the experiment, the distribution of flux densities of the spray were measured at a distance 2.0 m below of the nozzle. Input parameters used in the FDS model were obtained from the experimental measurements. These include flow rate of water, velocity of droplet, angle of sprays and height of spray. The numerical simulation was run and the distribution of flux density of the spray was calculated by the model.

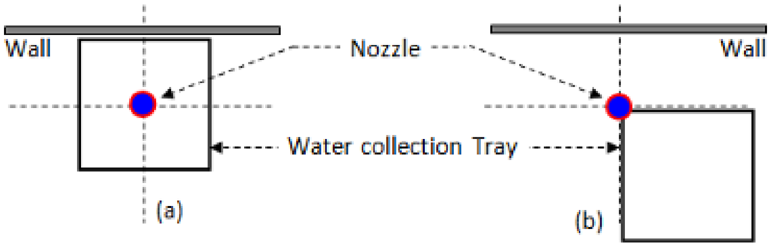


Figure 9: Locations of the nozzles (a) Case A; (b) Case B

The flux density distribution of experiment and numerical simulations were calculated in L/m^2/min and the contour maps for Case A are illustrated in Figures 10(a) and (b), respectively. The experimental results indicate that the distribution is ellipsoidal and the flux decreases with distance from the centre. The position of highest volume flux is displaced 20 cm from the centre of the tray in both the X and Y directions. A possible reason is that the spray is affected by the wall in the vicinity of the spray. A hint of this artefact is provided in the numerical results that also produced an elliptical flux distribution that is displaced towards the wall. In the numerical case, it is displaced by 10 cm.

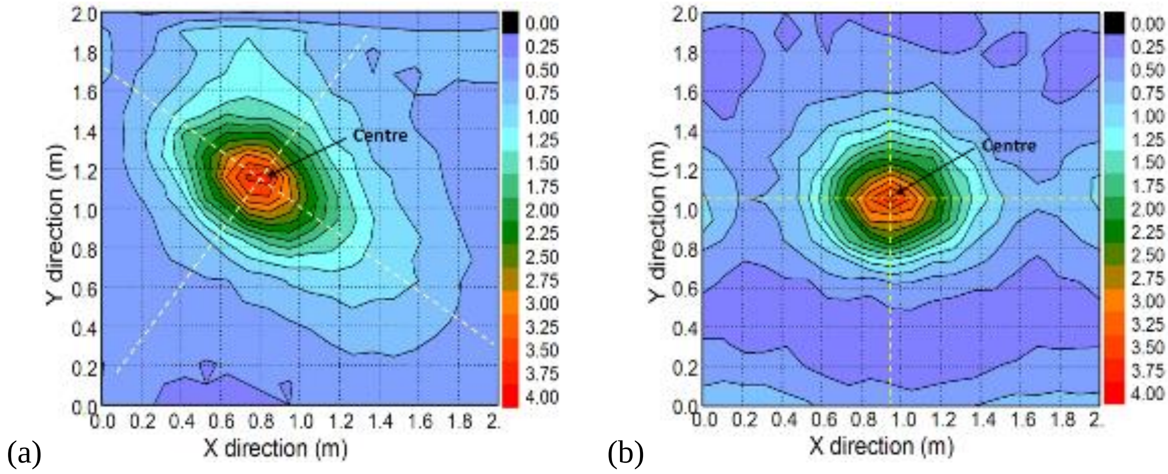


Figure 10: Distribution of flux density of spray for multi-orifice nozzle for case A;
(a) Experimental, (b) Numerical.

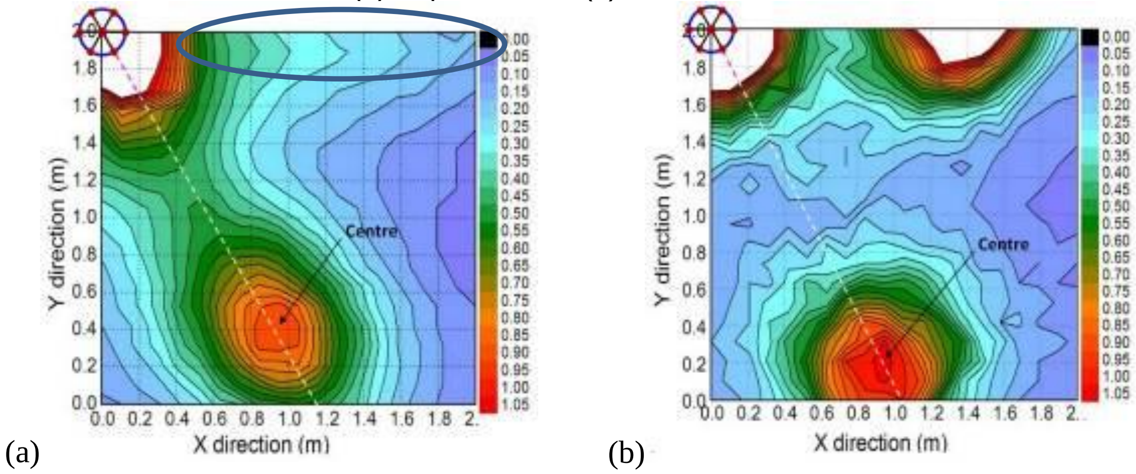


Figure 11: Distribution of flux density generated by a multi-orifice nozzle for case B;(a) Experimental, (b) Numerical.

The distribution of flux densities in the experiment and numerical simulation for Case B is shown in Figures 11 (a) and (b), respectively. The maximum flux densities of the sprays for the peripheral orifices are at locations (0.9, 0.4) and (0.9, 0.2) for the experimental and numerical distributions, respectively. The distributions generated by the sprays are elliptical for both experimentally and numerically generated sprays. The lateral contour axis is depicted by a line connecting the centres of the ellipses of distributions of sprays produced by the central and peripheral orifices. The distances of the centres of ellipses from the corner of the water collection tray along the lateral contour axis for the experimentally and numerically obtained distribution on the floor is 186 and 200 cm, respectively. The white colour in both of the figures is due to the reason that the flux densities in that region was out of scale (more than 1.05 L/m^2/min). The peripheral orifices in the body of the nozzle are oriented at an angle of 60° to each other. Therefore, it is expected that the angle separating the peripheral centre (topological) should also be 60°. This expectation is met by the numerical model in simulating the direction of spray produced by the individual orifices.

In Case B, one of the lateral contour axes was directed along an edge of the water collection tray and another one along a line at an angle of 60° to the edge as indicated in Figure 11. In the contour plot of distribution produced by the orifice whose axis was directed along an edge of the water collection tray, the half of the ellipse produced by distribution was captured on the water collection tray in the numerical model (Figure 11(b)); however, no such pattern was observed in the experimentally produced distribution (Figure 11(a)). A possible reason is that there was as wall 2 m away from the edge of the water collection tray and one of the orifices was directed to the wall. The droplet was injected from the nozzle with a high speed and it was spread in the room. As a result, it created turbulence in the space of the room. The turbulance created by the spray was affected by the presence of the wall. Moreover, as the droplet size is very small and light in weight, it was suspended surrounding the spray and scattered from its spray path due to the presence of the wall. As a result, no elliptical shape of spray was created by the experiment.

5. WILDFIRE MODELLING

Wildland fires/bushfires are the uncontrolled spread of fires that could occur in areas of the wildland-urban interface areas or wilderness. In recent events, bushfires have encroached on the built environment causing injuries, fatalities and loss of properties and eco-system. The fires caused in these areas can also impact on the viability of living in the surrounding areas. Although wildfire usually does not occur in tropical forests, due to climate change (more specifically lengthy dry season) in recent years Sundarban is experiencing wildfires (The Daily Star, 2016). In our research program, we focus on several major areas: flow through tree canopies, grassfires, effect of forest in slowing down surface fire, forest canopy fire and firebrands. Each of these subprojects can be considered as largely separate bodies of work within the larger area of CFD based modelling. In this paper, two subprojects will be discussed.

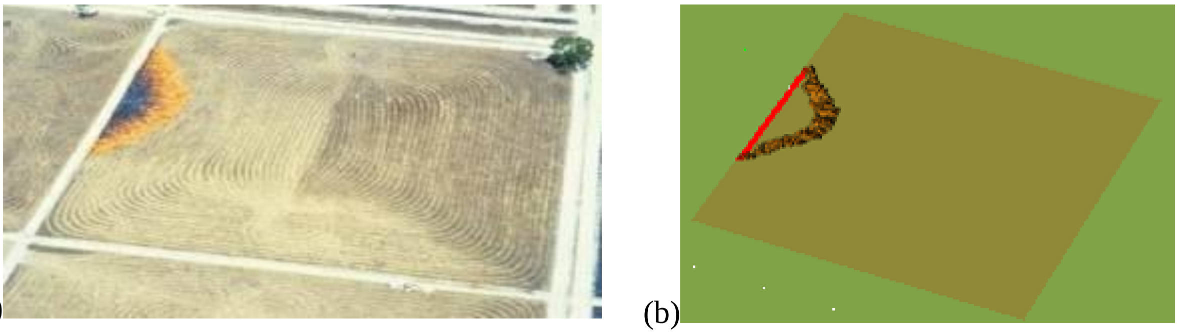
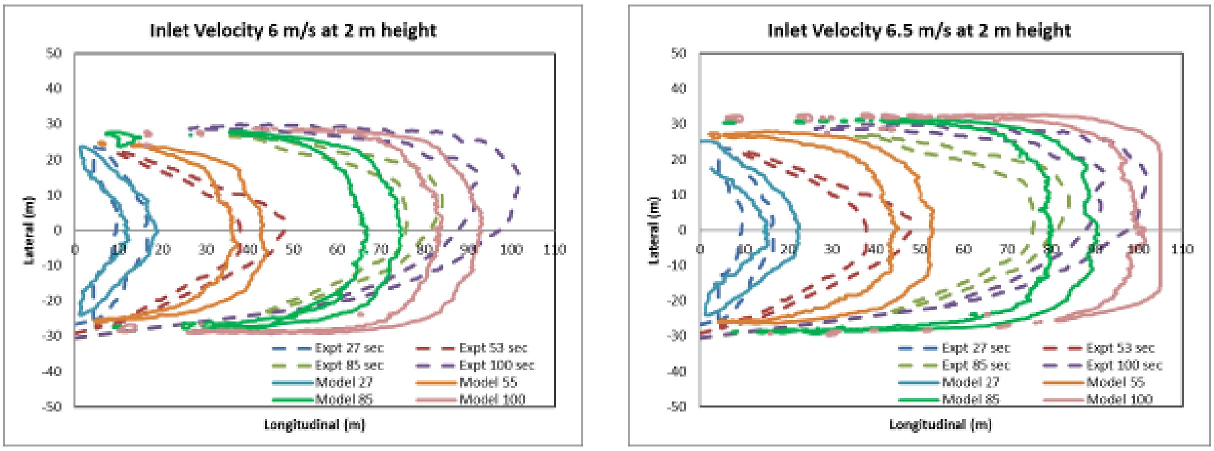
(a)  (b)

Figure 12: (a) Burning of Australian grassland and (b) CFD-based simulation

5.1 Grassfire propagation

Australian grassland fires were investigated by CSIRO researchers in Australia (Cheney et al, 1993) due to the simplicity afforded by relatively flat terrain and homogeneous fuel. Also, there is a number of experimental data available for validation. The rate of spread was considered a key factor that was studied in relation to these experiments. The Australian grassland experiment was conducted on a 104 m x 108 m plot 4.6 m/s wind was measured at 2 m above the grass surface blowing left to right. Ignition was started by two field workers at the centre of the left-hand-side. The workers then walked in opposite directions and took over 56 seconds to complete the line ignition. Figure 12 shows the experimental snapshots of the above mentioned experiment and CFD based simulation with WFDS.

In Figure 13 the fire perimeter propagation from experimental study and two simulations are presented. One simulation was conducted with wind velocity 6 m/s at 2 m height at the inlet and the other had 6.5 m/s wind velocity at the same location. The fire spread occurs from left to right. The fire perimeters are plotted 27s, 53s, 85s, and 100s after the ignition start. It observed that fire line progression is reasonably well predicted by the physics-based model.



(a) 6 m/s at 2m height at inlet (b) 6.5 m/s at 2m height at inlet

Figure 13: Model validation: fire propagation. Solid lines physics-based model result and dashed line experimental results-to be appeared in (Moinuddin, Sutherland and Mell, 2018).

After the validation of the WFDS model we attempted to see the effect of wind velocity and grassheight on the fire spread rate. We found that when wind speed is varied, the CFD-based model has predicted faster fire spread rate than a commonly used empirical model (known as McArthur Mk V model) (Moinuddin, Sutherland and Mell, 2018), but slower than a recently developed empirical model (known as CSIRO model) (Hollis, Gould, Cruz, and McCaw, 2015) as shown in Figure 14.

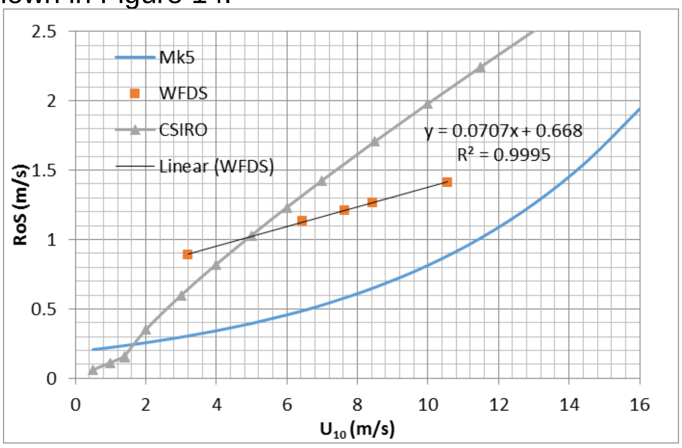
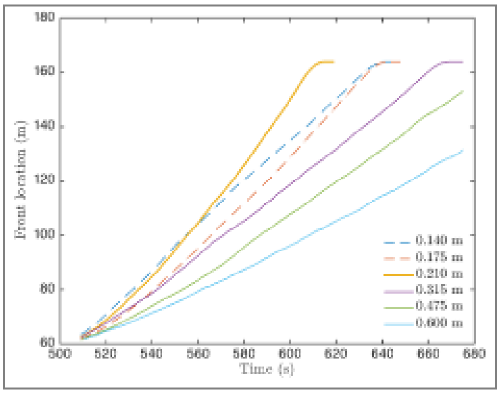


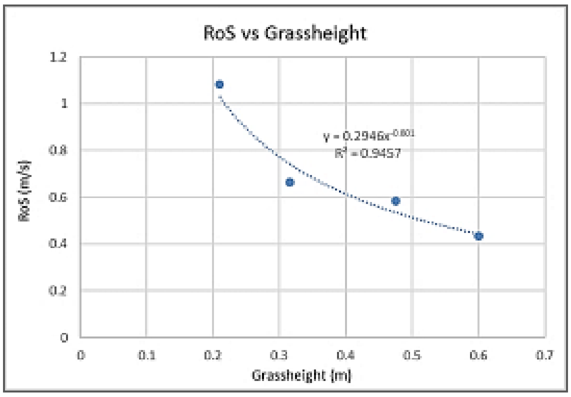
Figure 14: Effect of wind velocity on rate of spread (ROS)

However, the numerical results predict an unusually high rate of spread (ROS) when U_{10} (wind velocity at 10 m height). Furthermore, the numerical result is extraordinarily linear (though CSIRO model is also linear beyond 6 m/s U_{10}). Both aspects need to be further analysed. CSIRO model demonstrates two modes of propagations: boundary layer mode and plume mode (these are well known and discussed by Apte, Bilger, Green, and Quintiere (1991). At low U_{10} (5 m/s and below) the firefront is in the plume mode and beyond that the firefront is inclined by higher wind velocity resulting them into boundary layer mode.

To understand the effect of grass height, a set of simulations was carried out with six different grass heights: 0.1, 0.14, 0.175, 0.21, 0.315, 0.475 and 0.6 m at U_{10} of 6.5 m/s. Here the vegetation load is varied proportional to the grass height to maintain a constant bulk density. That is, the grass was not considered to be mowed and left on the ground. 0.1 m case shows fire self extinguishes at an early time. Examination of heat release rate demonstrates the two modes of propagation: the boundary layer mode with lower HRR (0.14 and 0.175m cases) and plume mode with higher HRR (four cases - 0.6, 0.475, 0.315 and 0.21 m) and correspondingly greater buoyant forces.



(a) Flamefront location



(b) RoS-Grassheight Correlation

Figure 15: Effect of vegetation height. To be appeared in (Moinuddin, Sutherland, and Mell, 2018).

In Figure 15(a), the locations of the head fire as function of time are presented for six cases (the slope of each curve represents RoS). Leaving aside the 0.14 m (boundary layer mode) and the 0.175 m (mostly boundary layer mode) fuel height cases, a clear trend in RoS emerges for the plume mode propagation (0.21 mm case onwards). In the plume mode (the 0.6, 0.475, 0.315 and 0.21 m height cases) the RoS decreases as the grass height increases. Physically these differences may be understood by considering the heat transfer from the flame to the unburnt vegetation. In the boundary layer mode the flame is inclined towards the ground and the virgin fuel ahead of the fire front, this leads to the unburnt vegetation receiving high net convective and radiative heat flux in the boundary layer mode. As a result, virgin fuel ahead of the fire front quickly undergoes pyrolysis and the RoS is large. Whereas, in the plume mode, the net heat transfer to the virgin fuel decreases as the flame becomes more vertical due to buoyancy induced flow toward the fire front. The lower heat transfer to the unburnt vegetation leads to a lower RoS. To develop a RoS-grass height correlation a least square method analysis is conducted in Figure 15(b) for each grass height in the plume mode. The calculation is based on when they reached steady state condition and a power law relation between RoS and grass height with an R^2 value of 0.95 is observed. A linear fit to the same data results in $R^2 = 0.83$. Ultimately, a much larger data set would be required to comprehensively establish a model of RoS in terms of grass height.

5.2 Effect of forest fire on bridges

WFDS/FDS is also capable to simulate forest fire growth and propagation. In this study (Dissanayake et al, 2018) wildland fire effects road infrastructures (steel plate girder bridges) is investigated. A 60m long and 10m wide and 25m high domain containing different fuel geometries and a bridge structure is simulated. 10m length portion of a 25m long and 11.5m wide composite steel plate girder bridge with 5 girders is modelled to represent a typical bridge structure. Temperature development of the structure is monitored using Adiabatic Surface Temperature (AST) computing devices (Wickström, Duthinh, and McGrattan, 2007) attached to various locations of the bridge. AST is a useful temperature that can be used in subsequent thermo-mechanical analysis of the bridge structure. Thermo-mechanical analysis is carried out using general purpose finite element software ABAQUS (Systèmes, 2013). A simple way to describe AST is as an imaginary temperature being used commonly for calculating both convective and radiative heat transfer to a Structural Model. AST provides an interface between fire and a structural model. The main advantage for utilizing AST is that only one quantity needs to be transferred from fire model to structural model.

The bridge structure is placed 32m away from the inlet boundary at the left-hand side. Grass strip starts 6m away from the away from the left side boundary. This gives the fire front to approach a steady state before reaching the bridge limit. Three scenarios were modelled:

(1) Case A: Wind velocity 10m above the ground is taken as 2m/s with only grassland around the bridge which resulted in a plume dominated fire.
(2) Case B: Wind velocity 10m above the ground is increased to 5 m/s altered the fire-atmosphere interaction from a more plume dominated fire to a wind dominated
(3) Case C: Wind velocity is 2 m/s with elevated fuel load present in the vicinity.

A graphical representation of typical distribution of surface and elevated vegetation fuel around the structure is presented in Figure 16 (a) – here Case C. Temperature development using heat transfer model within Abaqus FEM is presented in Figure 16 (b).

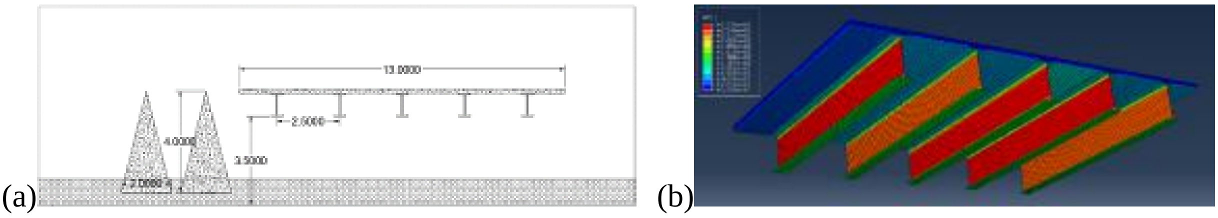


Figure 16. Models set up; (a) Distribution of surface and elevated vegetation fuel around the structure, (b) Temperature development of the heat transfer model in Abaqus FEM.

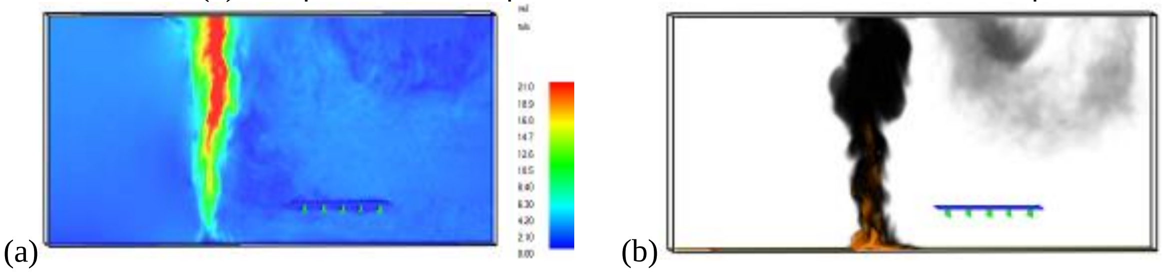
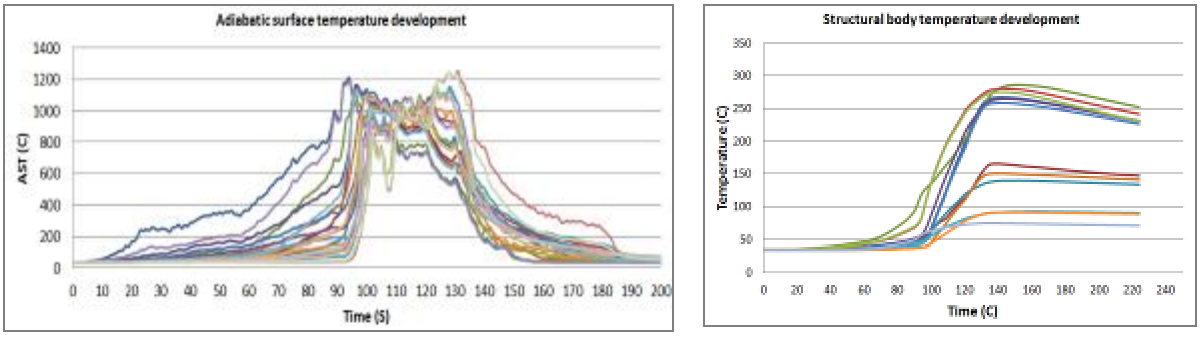


Figure 17. Velocity field and flame and soot distribution; (a) Wind velocity on the middle plane of the domain, (b) Fire plume and soot generation

A predominantly vertical velocity field and a vertical flame and soot distribution during Case A can be seen in Figure 17. The average fire spreading rate, estimated from visualisation of moving isosurfaces of HRR in Figure 17(b), is 0.3m/s within the entire domain.

Once the fire front enters under the bridge, the plume dominated fire starts to bend as a result of the overhead physical obstruction. This has increased the radiation energy transferred to the fuel bed in front of the fire front which has resulted an intensive burning and increased fireline intensity. The 11.5m width of the bridge does not allow the fireline intensity to reach a steady state value. AST of the structure was measured at the bottom surface of the concrete, mid height of the web and the flange bottom of each girder. Total sixty-six AST measuring devices are used to monitor the bridge surface temperature.

Average temperature development of each component is calculated using the results. Maximum AST reaches the value of 1200°C (Figure 18a). Peak temperature resident time is very short. The body temperature development of the structure can be grouped in to 3 categories as shown in Figure 18(b). Relatively lesser thickness of the web results a highest temperature development that reaches around 300°C. Bottom flange temperature development is around 150°C. Concrete bottom surface temperature barely reaches 100°C.



(a) Adiabatic surface temperature development of the structure

(b) Body temperature development of the system

Figure 18. Surface and body temperature: Case A

Graphical representation of flame and soot distribution from Case B and Case C is presented in Figure 19. The higher wind forces both the flame and the hot fire plume closer to the downwind fuel bed (Figure 19a) increasing both the radiative and convective heat fluxes. Rate of fire spread is increased to ~0.6m/s. That in turn results a less residence time even though the fireline intensity is increased compared to Case A. As a result, the adiabatic surface temperature that even reaches 1200°C results only lesser temperature development on the structure (Figure 20a). The highest temperature 200°C is recorded in the web of the structure. The concrete bottom surface temperature stays well below 100°C (Figure 20b).

Relatively low wind velocity in Case C gives rise to a nearly vertical flame front (Figure 19b). The average fire front progress rate is on average is the same as Case A (~0.3m/s). Adiabatic surface temperature has reached to 1400°C in some parts of the bridge (Figure 21a). Introduction of the elevated vegetation along with the surface fuel increased the amount of fuel present around the structure. This has caused more than 50°C temperature rise of the web when compared to Case A.

(a) (b)

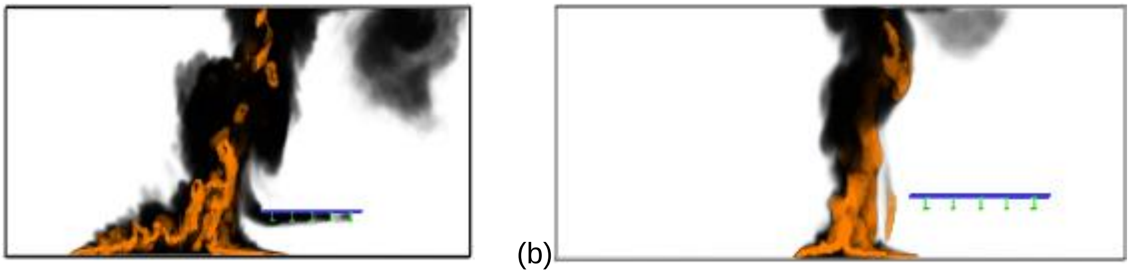
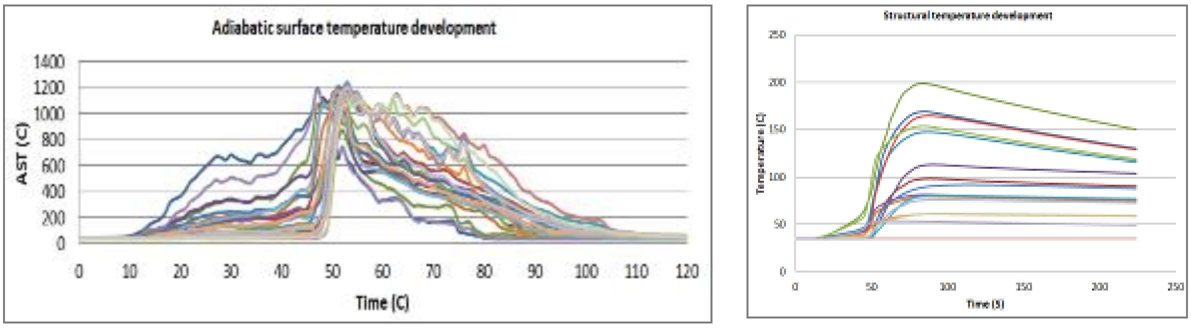


Figure 19. Fire plume and soot generation; (a) Case B, (b) Case C

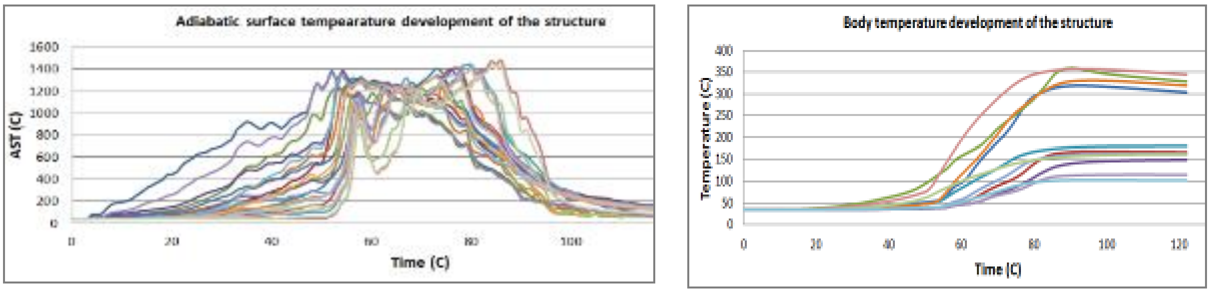
This preliminary study results show the temperature developments of the structural components could not lead to a residual strength degradation of steel or the cracking or spalling of the concrete. This is mainly due to the less flame resident time that didn't allow the temperature to build wishing the structure. However, the presence of elevated vegetation increases the risk significantly. Steel Young's modulus value will be decreased by 25% while the strength degradation of steel up to 400°C is limited. Further parametric studies are needed to have a clear conclusion. Further parametric studies are required to identify further critical fuel geometries around a bridge. Research results can help to predict the isolated and cumulative effects on a structure when exposed to recurrent WUI fire events in future.



(a) Adiabatic surface temperature development of the structure

(b) Body temperature development of the system

Figure 20. Surface and body temperature: Case B



(a) Adiabatic surface temperature development of the structure

(b) Body temperature development of the system

Figure 21. Surface and body temperature: Case C

6. CONCLUSION

Industrialized/developed nations has a priority to protect their human capitals, to save the lives of the workers and their supporting/supported families. As South Asian countries are rapidly transforming from agrarian economy to industrialized and service economy, trained workforce has become a valuable capital. Increasing literacy rate is leading to decreased fertility rate which is making protection of human capital even more vital. Climate change and energy demand are driving more sustainable built environment design. However, some initiatives of sustainability are increasing fire risks. There are building codes, regulations and guidelines used in advanced countries for the purpose of fire safety. It is important to realise that fire safety system design is only one part of the process – the design needs to be analysed to demonstrate that it can achieve acceptable level of fire safety. Generally sprinkler is known to be one of the most effective fire safety systems. Victoria University's research program on sprinkler system shows that the failure probability of the sprinkler system in a 60 storey Australian office building lies in the range 3% to 14% within which the commonly considered value (5%) in Australia falls. The testing program shows that in both open-plan and small office settings with high fuel load, once sprinkler is activated and delivers required amount of water it can effectively extinguishes the fire. CFD-based fire model, FDS is found to be reasonably model water distribution delivered by a water mist system. The model has also predicted the rate of spread of grass fire well. FDS model can be used to investigate wide range of building and wild fire scenarios and design effective mitigation system against such scenarios. The climate change and longer dry weather are making wildfire a possibility in tropical forests and it advisable that tropical nations prepare for it and work towards risk reduction.

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